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A DESIGN STUDY OF A 350 KWE OUT-OF-CORE NUCLEAR THERMIONIC CONVERTER SYSTEM

by Roland Breitwieser and Edward Lantz
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
Fifth Intersociety Energy Conversion Engineering Conference sponsored
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Abstract

Nuclear-thermionic systems with the thermionic converters outside the reactor have been re-examined in the perspective of several recent technical advances: new high-temperature, corrosion-resistant, high-strength alloys; high-heat-flux heat pipes; improved thermionic converters; and light-weight, vapor-cooled radiators. These have been combined to yield a new look to the out-of-core approach. A compact reactor results; insulators are eliminated by the use of heat pipes as electrically resistive elements; and weights are reduced by combining vapor-cooled radiators, structural supports, and current leads into vapor-cooled-radiator modules. The overall design is also highly modular and thus provides high reliability and a reduction in development costs.

Introduction

Development efforts in thermionic energy conversion have become almost completely focused on the use of thermionic converters located in the core of a reactor. But recently several technological advances have stimulated new interest in out-of-core thermionics: improved thermionic converter performance at low emitter temperatures; development of high-strength, corrosion-resistant, ductile, refractory-metal alloys; new methods of refractory metal fabrication by chemical vapor deposition; development of high-temperature, high-throughput heat pipes (ref. 1); new compact-reactor design concepts; the development of light weight multifoil insulation for high temperature use; and the evolution of light-weight vapor-cooled radiators. Some of these advances also benefit other space power systems, but the combination of the new technological advances exerts a unique impact on the out-of-core concept.

The application of the new technology to the out-of-core system described in this study followed the usual pattern. Previous designs were reviewed in detail to see whether simple upgrading of the parts would provide an attractive system. Many interesting concepts exist, but several stumbling blocks remain.

The biggest problem unique to out-of-core thermionics is the requirement of electrical isolation of the emitter of the converter from the heat source. Several past designs decouple the source of heat from the converter by use of radiant heat transfer. The various radiation coupling techniques (refs. 2-5) have one or more disadvantages: low power level (30-40kWe), reduced emitter temperature, bulky reactor, restricted shield configurations, large heat exchangers, and often a high specific weight.

Eventually a high temperature insulator may be achieved by using materials such as alumina or beryllia sandwiched between the emitter and the heat transfer tube. But at the present time the thin layers required for effective heat transport restrict the temperatures and voltages to conditions that impose significant performance penalties.

Another problem, common to many space power systems, is that complicated refractory metal structures, involved plumbing and bulky radiators appear at high power levels (100 to 500 kWe) and thus the early out-of-core concepts lose most of the simplicity and modularity found at low power levels. In addition, several designs for out-of-core systems would necessitate the development of a special reactor to circumvent problems of electrical isolation or some aspect of external complexity. In a pragmatic sense this does not appear desirable because of the high cost of reactor development.

The direction of this study was thus established: apply the new technology to cope with problems of electrical isolation, use a reactor that is adaptable to a range of power levels as well as other conversion methods, and design a system that scales by modularity. The term modularity implies that the system is based on small, largely independent building blocks. The coupling of the building blocks must also adapt to modular, small-scale tests. Any advanced system will introduce engineering uncertainties, thus ease of testing and ease of scaling is emphasized.

Design Approach

The general design of the system presented in this paper was influenced by the approach used by Loewe (ref. 6). It differs in that long heat transfer tubes (heat pipes) are used to provide electrical isolation between the converters and the heat source and a different reactor heat exchanger design approach is used. The preoccupation with modularity encouraged these changes.

Assumptions

Several assumptions that are somewhat arbitrary immediately constrain the characteristics of the system. They are the following.

1. System output power of 350 kWe at 28 volts or greater.
2. A maximum temperature of 1800° K assigned to the long converter heat pipe.
3. Maximum launch vehicle diameter of 30 ft.
4. Radiation from both sides of the radiator.
5. System adaptable to a man rated shield (4π and modified 4π) and an instrument rated shield.
6. Intermediate heat exchanger located between the reactor and shield.
7. Redundancy as well as modularity required in the shielded heat exchanger.
8. Two-fold redundancy of the 28 volt array required.
9. Thermionic converter performance limited to that typical of 1969 research converters.

With these assumptions some geometrical and numerical constraints exist. For example, the assumption of two-fold redundancy for producing 28 volts and the use of multiple banks of converter pipes for redundancy in the cross flow heat exchanger specify the number of converter and reactor heat pipes. The number of heat pipes along with the power level, conversion efficiency and radiator characteristics establishes radiator and radiator module dimensions. Thus a major part of the system design becomes established.

Description of the System

Figure 1 shows one form of the proposed system. The various sections of the drawing illustrate the arrangement of the parts. They are the following.

Section A (fig. 1): An assembly of hexagonal reactor fuel elements containing small diameter heat pipes, confined by an external reflector. The reactor is split and the two ends are symmetric and are electrically isolated from one another.

Section B (fig. 1): A cross flow heat exchanger consisting of 17 rows of reactor heat pipes. The reactor heat pipes (fig. 2) are cylindrical in the reactor fuel area and transform into a rectangular shape to form the walls of a flat plate heat exchanger. The heat exchanger is sufficiently long to receive three rows of the heat pipes that lead to each converter bank. The ends of the converter pipes are flattened in order to improve thermal contact with the reactor pipes. Multiple rows provide power smoothing in the event of failure of one or more heat pipes.

Section C (fig. 1): Nestled converter heat pipes. The converter heat pipes retain their rectangular shape as they penetrate the shield and are clustered in four groups of 24 pipes. Difficulty in balancing areas and power density causes variations in the heat flux in the heat exchanger. Clustering helps smooth power variations in the reactor heat exchanger and reduces the shield penetration cross-sectional area.

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Section C (fig. 1): Nestled converter heat pipes. The converter heat pipes retain their rectangular shape as they penetrate the shield and are clustered in four groups of 24 pipes. Difficulty in balancing areas and power density causes variations in the heat flux in the heat exchanger. Clustering helps smooth power variations in the reactor heat exchanger and reduces the shield penetration cross-sectional area.

Section D (fig. 1): Isolated heat pipes. At a point external to the shield the pipes plus their thermal insulation and armor for protection against meteoroids form a spoke-like array that carries heat to the converter, provides electrical isolation between the converters and heat source, and serves as a structural support for the radiator-converter assembly.

Section E (fig. 1): Converter-radiator. The heat pipe serves as a part of the emitter structure for a bank of eight converters electrically connected in parallel. The compartmented vapor fin radiator serves the additional role of an electrical lead to the adjacent bank of converters. The converters are arranged to form a cylindrical or flat plate radiator.

Reactor Shields

Man-rated reactor shields are heavy and dominate the weight of a nuclear power system, thus, before analyzing the reactor or converter elements the interaction with the shield must be established. For example, shields that exert a significant effect on this system optimization are a 4π man-rated shield that limits the dose rate to 2 mr/hr at a separation distance of 100 ft and a modified 4π man-rated shield that limits the dose rate to 2 mr/hr in a 10° $\frac{1}{2}$ angle cone and 1 r/hr elsewhere. The shield weight estimates use several alternate layers of depleted uranium and lithium hydride to achieve the required neutron and gamma attenuation. The layer thicknesses and locations are based on reference 7. The weights of several shields for different core sizes and reactor thermal power levels were calculated. An empirical expression that fitted the specific calculations was then determined. The effect of reactor thermal power (thus conversion efficiency) and size was characterized by a simple three term expression which was used to adjust and optimize specific weights. Fortunately the number of iterations required to determine optimum weights was small since the effect of conversion efficiency on the shields selected is not strong. A conversion efficiency of 11.9% was selected for most cases examined.

Shield weights for several core diameters are shown in figure 3. Volumes for a compact and a derated heat exchanger (discussed in a later section) are included in the reactor shield weights. Although the relative change in shield weight with core diameter is small, the absolute change in weight is significant and makes the small cores attractive.

Converter Heat Pipes

The characteristics of the system are strongly influenced by the long converter heat pipes. The practicality of these heat pipes is in part supported by review articles on heat pipes presented at last year's conference (refs. 8 and 9), a recent analytical treatment of long lithium filled heat pipes (ref. 10), recent corrosion studies of refractory metals in the presence of alkali metals (ref. 11), and creep data for tantalum base alloys (ref. 12). A temperature of 1800° K for the heat pipe vapor and a maximum hoop stress of 540 psi in the containing walls were chosen as guidelines in the heat pipe analysis.

The electrical arrangements considered are schematically shown in figure 4. A set of 12 banks of converter pipes is connected in series at the radiator. The voltage developed and the local leakage paths are shown in figure 4. Using the reactor as a centrally located, common ground results in an output voltage of 14.64 volts for the 24 banks . The two halves of the reactor are electrically isolated, as are the heat exchangers so that this system output voltage is 29.23 volts.

The electrical leakage loss along the heat pipe is proportional to V^2/R . Although it would appear desirable to increase the length of the heat pipes to minimize the electrical losses, this can be achieved only within certain limits. Pressure drops associated with long pipes require an increased diameter in the adiabatic section in order to remain within the capillary pumping capabilities of the pipes. This results in increased heat pipe weight as well as increased armor weight due to the larger vulnerable area.

The various relations governing electrical leakage, stress, heat pipe pumping limits, and temperature losses were used to determine a first order estimate of the effect of length on the electrical power loss of arrays of heat pipes at a maximum potential of 29 volts. An axial throughput of 30 kWt was assumed, which is approximately the value used in the system analysis. The results are given in figure 5. Fabrication and reliability limit the wall thicknesses that can be used in refractory metal tubes, and frictional effects limit the diameter. The minimum length feasible appears to be around 250 cm. The power loss at this length due to resistive heating is about 8%. The specific weight of this pipe including multifoil insulation is about 1 lb/kWe. Although the power loss is lower at greater lengths, the influence on system weight must be recognized. For purposes of comparison, a power loss of about 8.0% is equivalent to about one percentage point change in the conversion efficiency of the thermionic converter. In turn, a reduction in efficiency from 12.5 to 11.5% is equivalent to an increase of only 3.4 lbs/kWe for a 4π shielded, 30 cm diameter reactor core. Furthermore, the specific weights given in figure 5 do not include allowance for armor. The armor weights are dependent on the configuration of the power plant and thus are difficult to treat in a general fashion. Several cases for typical installations indicate the requirement of armor doubles the values shown in figure 5. Thus, for a minimum weight system it is desirable to avoid very long pipes and sacrifice some efficiency.

Converters-Radiator

The converter design proposed for the system is shown in figure 6. This converter is similar to a converter undergoing tests at the Lewis Research Center. Salient features of the converter are

1. an oriented (0001 Miller index) rhenium emitter, 2.4 cm in diameter, deposited on a tantalum substrate;
2. a niobium collector spaced 8 mils from the emitter;
3. a compacted cermet (made of Al_2O_3 coated niobium spheres) insulator; and
4. a sodium, compartmented, vapor fin radiator, 44 cm (17 inches long).

The design permits pretesting of the converter and integral radiator by electron bombardment heating. After successful testing the converter is subsequently shrunk onto the tantalum base alloy heat pipe. Eight diodes, each 15 cm (5.9 inches) long, form a complete heat pipe bank producing 3.65 kWe. The heat pipe and converter bank can also be pretested prior to system assembly.

The design of the converter part of the converter radiator assembly was based on the performance values given in references 13 and 14. These data were compacted into empirical expressions that permitted maximizing efficiency and minimizing weight as a function of diode size and operating conditions. The optimum converter specific weights for the three shield cases considered include the interrelation of shield weight and conversion efficiency.

Converter-radiator specific weights for optimized configurations including interconnecting lead losses, voltage drops in the electrodes, temperature drops across the emitter, and end losses are as follows.

SHIELD TYPE	CONVERTER-RADIATOR SPECIFIC WEIGHT
Instrument	9.08 lb/kWe
Modified 4π	9.75 lb/kWe
Full 4π	9.75 lb/kWe

The efficiency for the heavier shielded applications is about 12.3%, about 0.2 of a percentage point higher than for the lighter instrument shielded application. Both of these calculated efficiencies are about 25 percent higher than those measured in cylindrical converters at this Center. The electrode materials of the new planar diodes (refs. 13 and 14) support the use of the calculated values. It is interesting to note that the specific weights are about the same as a bumper-fin, conductively cooled radiator projected for use in in-core thermionics or Rankine space power systems.

This result is not surprising because 1) high-temperature lithium and sodium heat pipes are two of the most effective heat transfer devices, 2) the isothermal feature of the lithium heat pipe and sodium-vapor chamber fin improves radiator surface effectiveness, 3) the emitter and collector surfaces provide all meteoroid armor necessary to protect the heat pipe, 4) the fin and heat pipe arrangement is highly redundant, and 5) the end design uses the electrical lead to protect the expansion elements, again eliminating the need for extra armor.

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Reactor Heat Exchanger

Reactor - A heat pipe cooled, vented, fast-neutron, reflected reactor was used in this study (figure 7). Heat pipes were selected because of the following characteristics:

Redundancy and safety. - The large number of independent, sealed elements provides enough redundancy to minimize the probability of a catastrophic coolant loss accident. The fuel elements are in contact (figure 7) so that, if occasional local failures occur, only a minor excursion in temperature results.

Pumping. - The usual electromagnetic, EM, coolant pumps are eliminated. This results in savings in the electrical power required to operate low efficiency EM pumps, and the elimination of the shielded volumes required to house the pumps.

More uniform reactor temperature. - The heat pipe reactor should reduce temperature variations along the length of the core. This curtails the mass transport of the reactor materials and should increase the average reactor temperature for a fixed maximum fuel temperature.

Partial power operation. - The heat pipes should allow the system to run at a much lower power level than attainable in a pumped loop that does not have an auxiliary source of power. Thus the reactor afterheat could be inherently taken care of with almost no probability for a core meltdown.

Testing. - The highly modular character of the reactor (and heat exchanger) permits tests of single elements and clusters of elements to be conducted rapidly and inexpensively in small scale facilities.

As in reference 15, very high axial heat transfer rates from the reactor are achieved by connecting heat pipes to heat exchangers located at both ends of the reactor. However, in our concept the reactor is built in two noncritical halves. Reactivity control is established by the relative position of the two halves. The split reactor and independent heat exchangers also provide for easy electrical isolation of the two sections. Thus higher system voltages can be obtained by isolating two sets of heat pipes as discussed in an earlier section.

The influence of core size and fuel type on the heat transfer, critical fuel mass, and weight of the reactor was examined for two fuels, U-233 and fully enriched U-235, both in the monocarbide form. The core length was assumed equal to the core diameter. The type of reflectors used are shown in figure 7. The influence of fuel burnup on fuel swelling is difficult to predict since little data exist for the time at the temperatures of interest. It was therefore assumed that a void space equal to 30 percent of the fuel volume was available for fuel swelling. Another 10 percent of the reactor volume was allocated to tungsten that could be introduced either in or around the fuel. The remaining reactor volume was assigned to lithium filled tungsten heat pipes. The U-235 fuel mass and volume distribution required to maintain criticality for an extended-life reactor of this type is shown in figure 8. Smaller cores are, of course, available with the use of U-233 fuel.

Reactor heat exchanger - One of the more difficult problems in most high temperature space power systems is the mechanical design of the refractory metal heat exchanger. A single faulty weld in a complex metal structure can cause failure of a major component or the entire system. This is an area in which we believe the design used in this paper introduces an interesting solution. As shown in the layout drawing, figures 1 and 2, the cylindrical heat pipes in the reactor penetrate the tungsten axial reflectors and extend into the heat exchanger area. The heat pipes form the walls of a modular, flat-plate, cross-flow heat exchanger. The reactor heat-exchanger heat-pipe shell is made of chemically vapor deposited (CVD) tungsten. The CVD process permits the easy fabrication of the somewhat unorthodox shape. The heat exchanger is completed by inserting flattened ends of the converter heat pipes in a multilayered fashion shown in the layout drawing. Thermal contact between the surfaces is maintained by an external hoop that surrounds the reactor heat exchanger. The hoop is kept at a temperature equal to or slightly lower than the converter heat pipe temperature, and thus a thermally stable heat exchanger should result.

Several unique features of the heat exchanger are 1) low probability of failure due to the very few welds in any of the modular elements; 2) accommodation of local failure, if it occurs, through redundancy; 3) ease of fabrication, test, and assembly of the independent modules in the decoupled reactor and converter heat pipe sections, and 4) finally a uniform temperature and small temperature drops resulting from the condensing, evaporative method of heat transfer in the mutually coupled, yet independent elements.

Reactor-heat exchanger characteristics - The temperature difference between the peak fuel temperature and the evaporating surface in the converter heat pipes was calculated for the two fuels at several core diameters. Uniform volumetric heat release in the core was assumed. Tightly packed fuel segments that are externally constrained were assumed to maintain contact with the heat pipes. A collet like configuration serves to maintain this contact and provide passages for fission gas release (figure 7). The effect of imperfect contact between the fuel and the heat pipe was treated by decreasing the metallic heat transfer coefficient by 15 percent.

The heat exchanger dimensions were adjusted to maintain the lithium vapor velocity and surface heat flux rate well below experimentally observed values. With the assigned temperature of the converter heat pipes, 1800° K for evaporating surface of the lithium, the peak fuel temperature was determined. The temperature varied from 2066° K to 2038° K as U-233 fueled reactor core diameter changed from 24 to 32 cm. The reduced heat-pipe volume that exists with the less reactive U-235 fuel raised the temperatures. The highest temperature calculated was 2110° K for a 26 cm diameter, U-235 core.

The nonuniform volumetric heat release in actual operation will of course increase these values. These results are presented to show that the first order estimates predict moderate peak fuel temperatures and that the variations in temperature with reactor size and fuel type are not large.

The specific weight of the bare reactor including reflectors and heat exchanger but excluding weights of control hardware is given in figure 9.

Included in figure 9 are reactor weights for a derated heat exchanger. The heat exchanger length was abitrarily increased by 1.5 to explore the sensitivity of this design change on reactor and reactor-shield weights; little change in these weight results. Also, little change in reactor specific weight exists between the two fuels for a fixed core size.

The number of pipes and the volume available for the pipes establish the minimum size core that is feasible on the basis of either heat pipe fabrication constraints or axial heat transfer limits. The minimum core diameters are about 26 cm for U-235 fuel and 24 cm for the U-233 fuel.

The reactor design and characteristics were based on the assumption of a constant heat exchanger discharge temperature. This assumes the operating temperature of the converter heat pipes is the limiting factor in the design. If this premise is incorrect the system will probably be limited to a peak fuel temperature. Since a peak fuel temperature limit causes changes in shield weight through changes in conversion efficiency the effect of a constant peak fuel temperature was explored, and for the temperatures variations observed only about ±3% change in a 4π shield weight was noted. Thus the trends of this system study are equally applicable with the assumption of either a peak fuel temperature or a maximum converter heat pipe temperature.

Illustrative Systems

The specific weights that are estimated for the major components of two applications of the out-of-core modular concept are given in Table I. The applications are a man-rated shielded reactor combined with a cylindrical radiator (figure 10) and an instrument-rated shadow shield (figure 11). The tinker-toy-like assembly of the modular elements permits many variations in the radiator arrangement. These figures are just two of many examples.

Man-rated shields - Two reactors were selected: a 26 cm, U-233 fueled core and a 28 cm, U-235 fueled core. Both are 2 cm larger than the ideal minimum cylindrical core in order to accommodate geometrical irregularities of the hexangular fuel forms and box-like heat exchanger elements. A derated heat exchanger was also used in order to establish some conservatism for man-rated systems. The specific weights of the two reactors are small.

The dominant weights of the system are in the shield. The main influence of reactor size on system weight appears in the effect on the shield. The full 4π shield weights can be reduced by shaping the shield as discussed in a previous section. The reduced shield specific weights for the modified 4π shield are included in Table I.

The long converter heat pipes leave the reactor heat exchanger then bend to reduce the streaming of nuclear particles through the shield. The bend also accommodates mismatches in the thermal expansion of the heat pipe and surrounding parts. The converter heat pipes enter separate multifoil insulated aluminum pipes at the surface of the shield. The 0.41 cm (5/32 in) thick aluminum walls provide meteoroid protection and support the radiator-converter assembly.

The length of the electrically isolated portion of the heat pipe is 366 cm (12 ft). At an output voltage of 29.7 volts a 7% loss in the heat pipes result. A detailed matching of heat pipe lengths and diameters will yield slightly lower losses.

The converters are arranged in a 670 cm (22 ft) diameter cylinder that is about 240 cm (8 ft) long. Two specific weights are given in Table I; the higher value includes electrical losses in the heat pipes.

Instrument-rated shield - The reactor selected for the specific weight estimates uses U-233 fuel, is 26 cm in diameter, and is based on a compact heat exchanger. A low reactor specific weight results (Table I).

The shield weights estimated for a non-manned mission are highly dependent on the radiation susceptibility of the instruments. It is assumed that the radiation dose rate is 1 rad/hr at a distance of 100 ft. The shield used also provides a radiation shadow sufficient to hide the flat segment of the disc-like radiator. As this discussion indicates the specific shield weights for the instrumented application are only first order estimates.

The shadow shield configuration requires longer, larger heat pipes than the man-rated application (figure 11). The increased area exposed to possible meteoroid damage requires thicker armor. Since the heat pipes leave the shield in a manner similar to that for the man-rated shield, differences in armor weight appear mainly in the increased thickness of the aluminum tubes used to protect the heat pipes and support the radiator. The specific weights for this application are over two times that of the man-rated shield.

The converters (and integral radiator) are lighter than those selected for man-rated systems. The specific weight including recognition of a 7¼% loss in the heat pipes is less than 10 lb/kWe. Again the loss may be reduced by a detailed adjustment of the diameters of each set of heat pipes.

TABLE I

A. Man-Rated Systems

ITEM			SPECIFIC WEIGHT lb/kWe
Reactor	U-233, 26 cm core		3.85
	U-235, 26 cm core		4.5
Shield	Full 4π	U-233	211.3
		U-235	218.8
	Modified 4π	U-233	96.0
		U-235	99.0
Converter Heat Pipes			2.0
Heat Pipe Structure and Armor			1.2
Converter (and integral radiator)			9.75
Converter (with heat pipe penalty)			10.4

B. Instrument-Rated System

ITEM		SPECIFIC WEIGHT lb/kWe
Reactor	U-233, 26 cm core	3.5
Shield		7.3
Converter Heat Pipes		2.0
Heat Pipe Structure and Armor		3.0
Converter (and integral radiator with heat pipe penalty)		9.7

The specific weights of the primary parts of both applications are quite modest. The total weights of a fully engineered system are of course greater than the sum of the primary parts listed in Table I. The additional weights have not been included since they are so strongly interrelated with the design of the vehicle and the end use of the power.

But in the spirit of comparing various energy conversion techniques the following approach is used. We note that, to a certain extent, this paper advocates a new compact heat-pipe cooled reactor design based on modular elements that reduce development costs and possess a large amount of redundancy for system reliability. Fortunately, this reactor design adapts to most external conversion techniques.

The potential reliability of this modular reactor lends itself quite naturally to high temperatures. And in the framework of new performance improvements of thermionic conversion we can project an integral radiator, thermionic-converter design that weighs about the same as the radiator alone of competitive systems. Perhaps most important of all, modularity is retained all the way to the point of heat rejection if out-of-core thermionics are used.

Concluding Remarks

Recently a combination of engineering advances has brought about a revival of interest in out-of-core thermionics. Information on corrosion, strength of materials, vapor-phase heat transfer, improved converter performance and reactor-fuel stability has been combined to make some of the old concepts more attractive. But of more importance, the new information has stimulated innovative approaches. Coupled with new concepts in modular design and testing, out-of-core thermionics may provide an effective, reliable, multi-purpose power plant.

The space power system suggested in this paper is a deliberate attempt to move system designers and potential users away from their usual patterns. Split reactors, metal tubes used as insulators, small-bore reactor heat-pipes, decoupled components, flexible configurations, tinker-toy-like assembly procedures, multi-use elements were approaches used. Although the particular systems illustrated may have their faults, out-of-core thermionics using the advanced technology of the 1970's should prove to be strong contenders for nuclear-space power.

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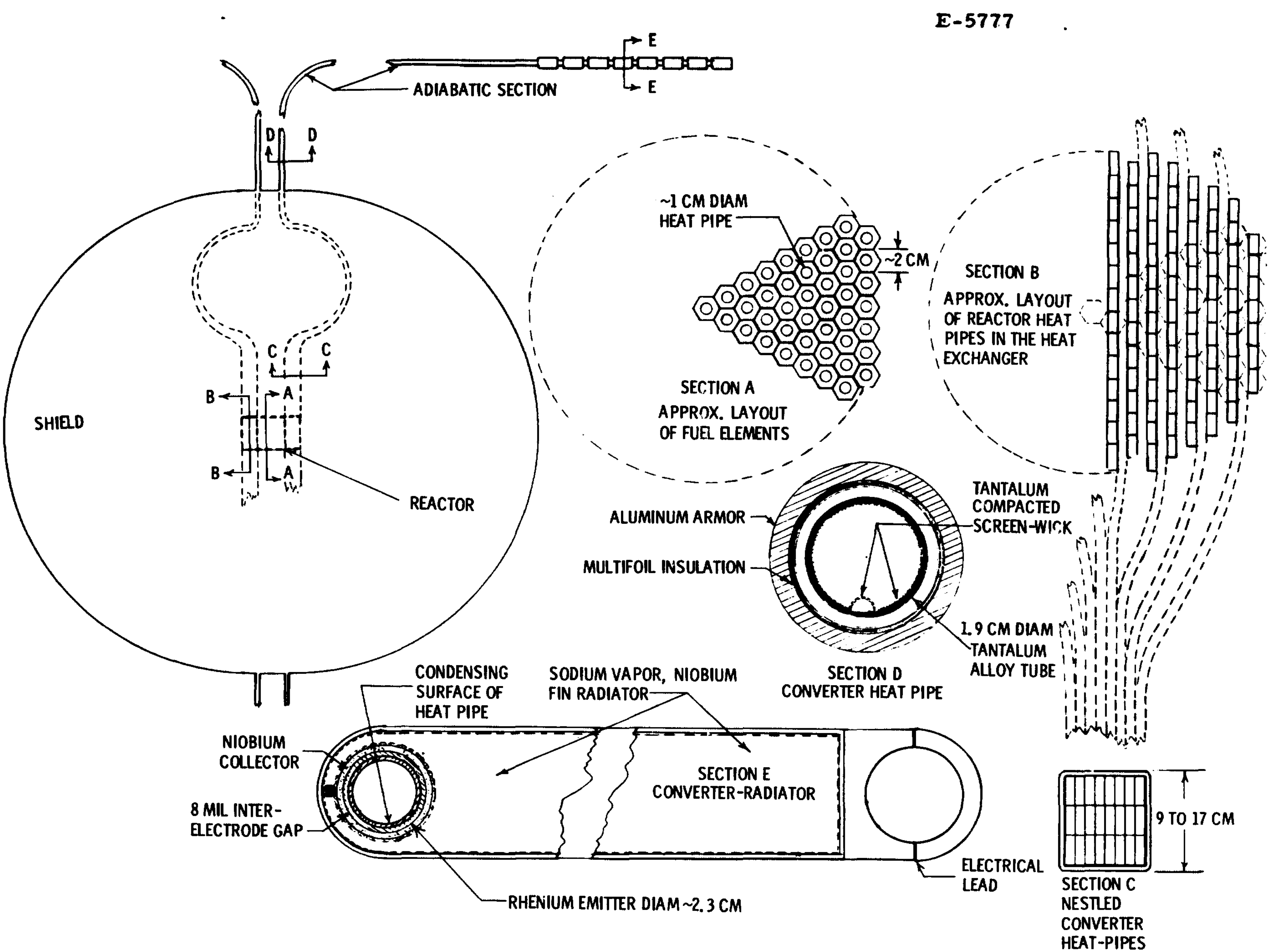

Figure 1. - Approximate arrangement of the primary parts of a 4π man-rated shielded reactor with an out-of-core thermionic conversion system.

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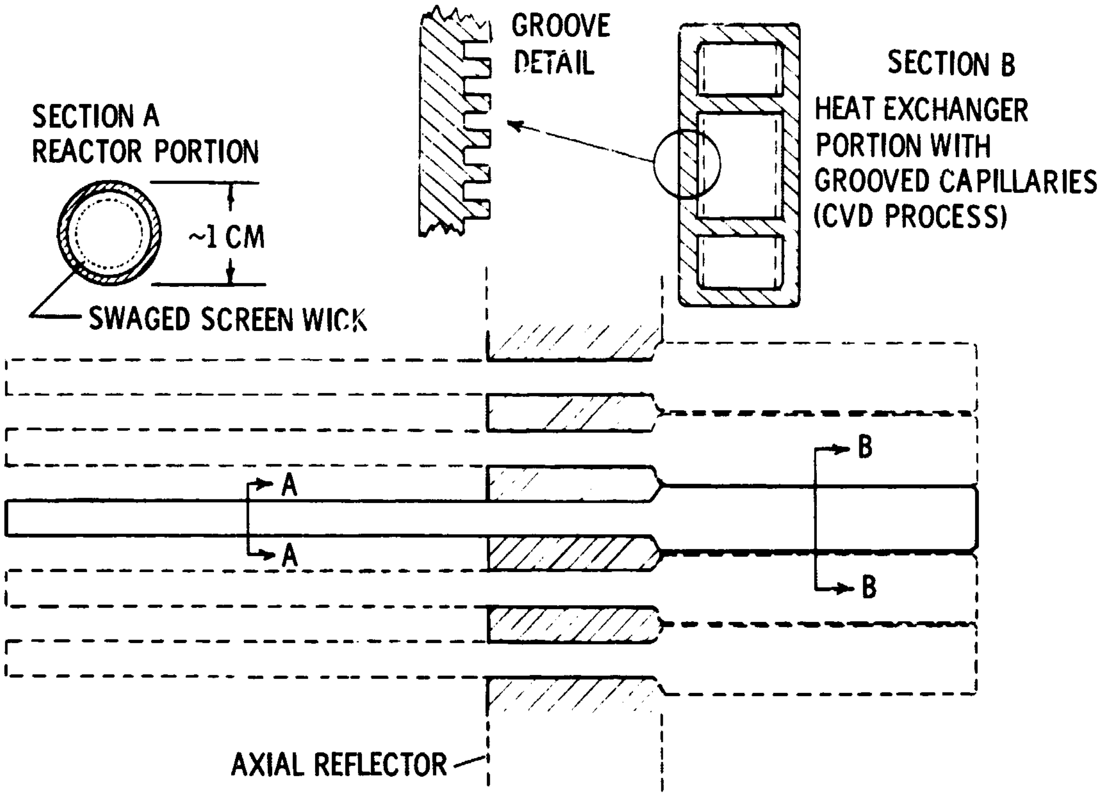

Figure 2. - Details of the tungsten reactor heat pipes.

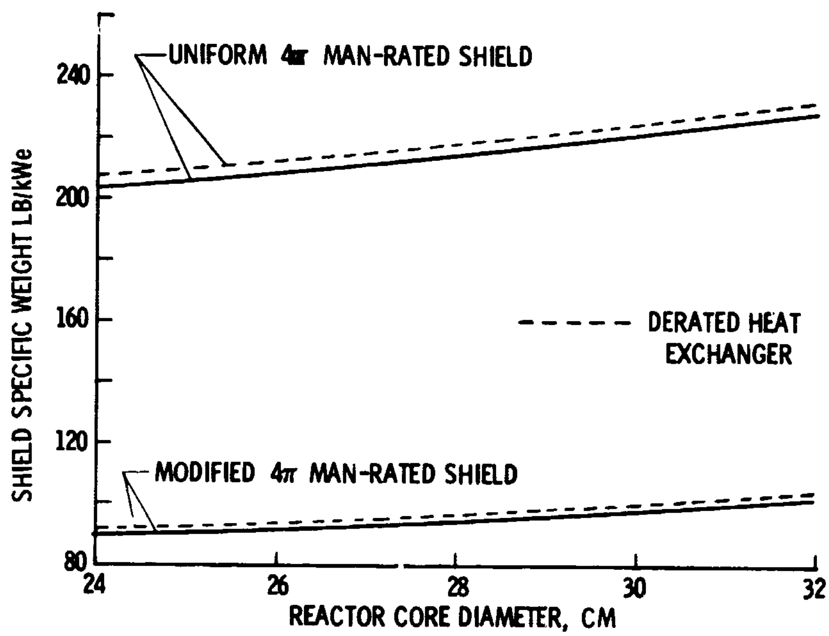

Figure 3. - Effects of reactor-heat-exchanger and core sizes on shield weights.

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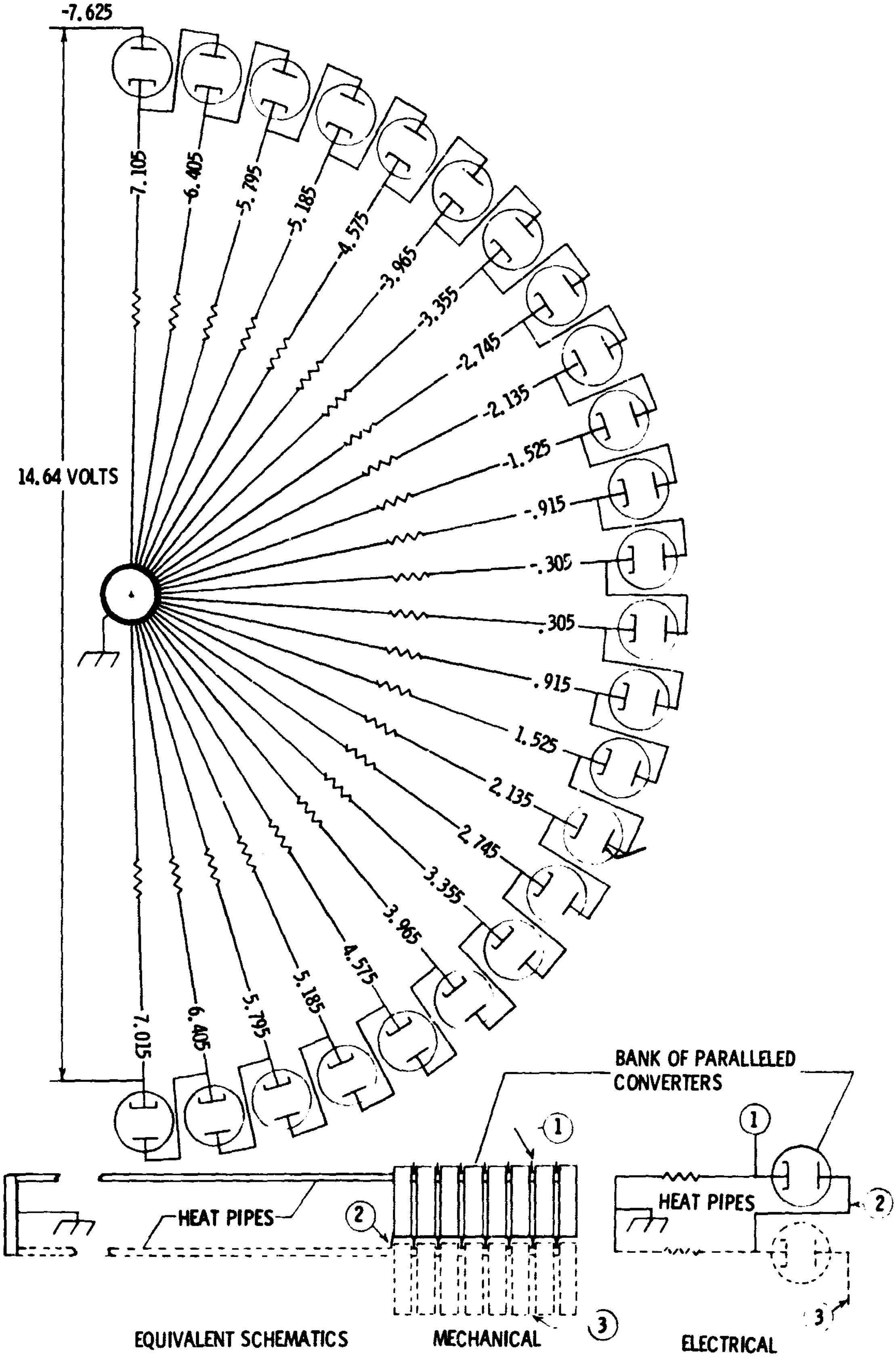

Figure 4. - An example of how heat pipes can be used for electrical isolation. Four sets of 12 banks provide 29.28 volts.

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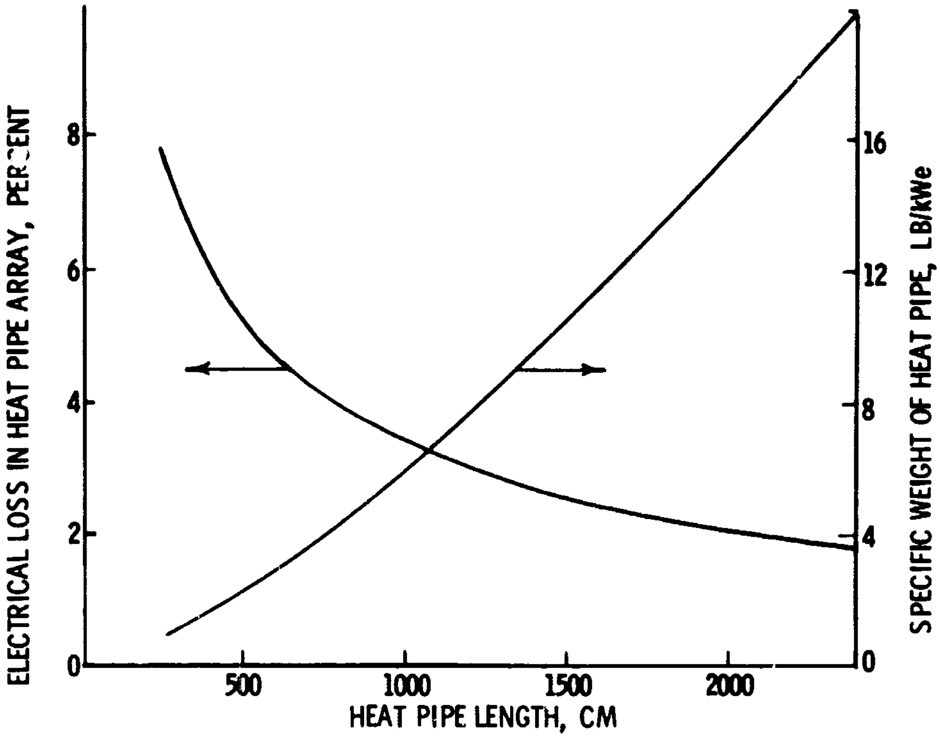

Figure 5. - The effect of heat pipe length (with an optimized diameter based on stress and capillary pumping limits) on the electrical losses and on specific weight for an array of heat pipes producing 29 volts (a local voltage of 7.25 volts in a single set).

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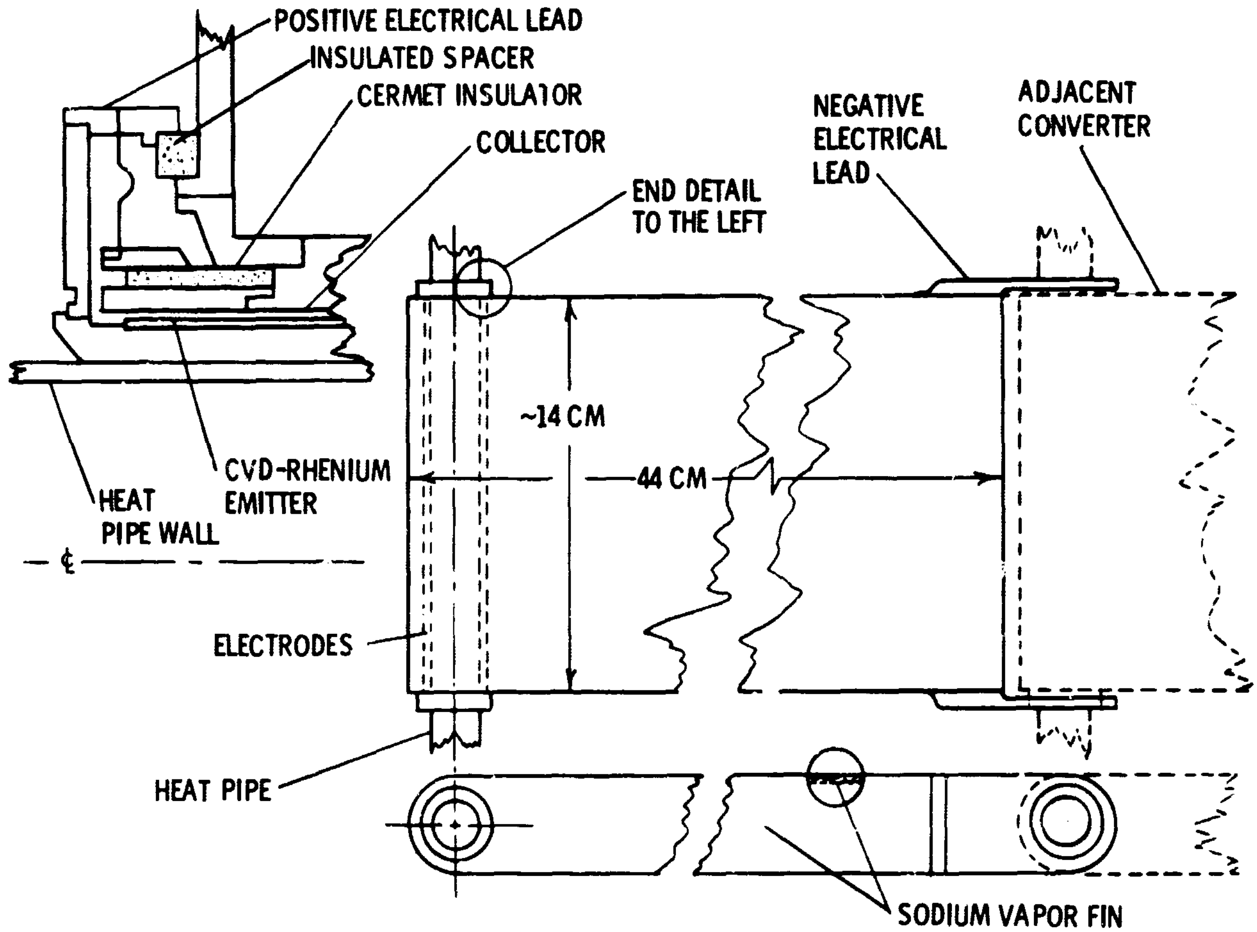

Figure 6. - Thermionic converter and integral vapor fin radiator.

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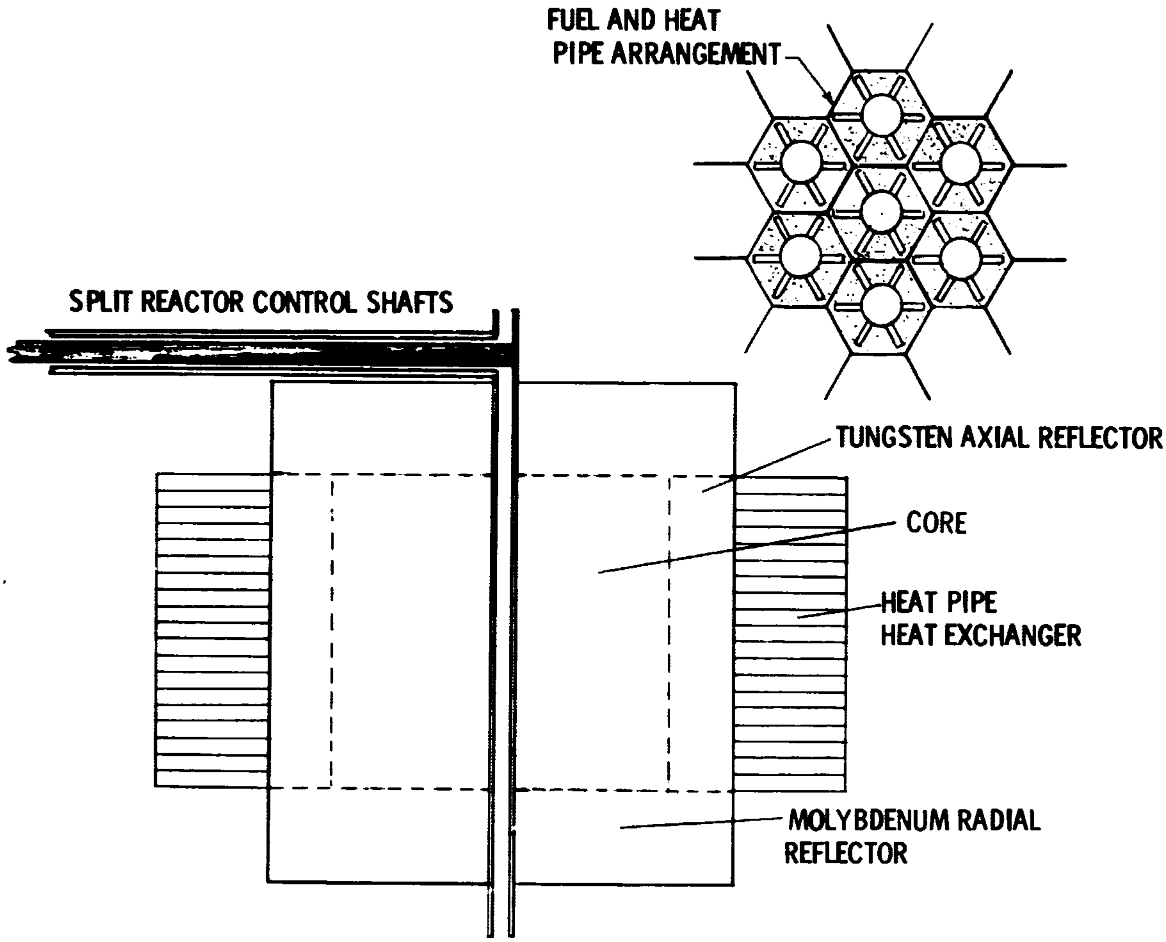

Figure 7. - Diagram of the reactor and reactor heat exchanger.

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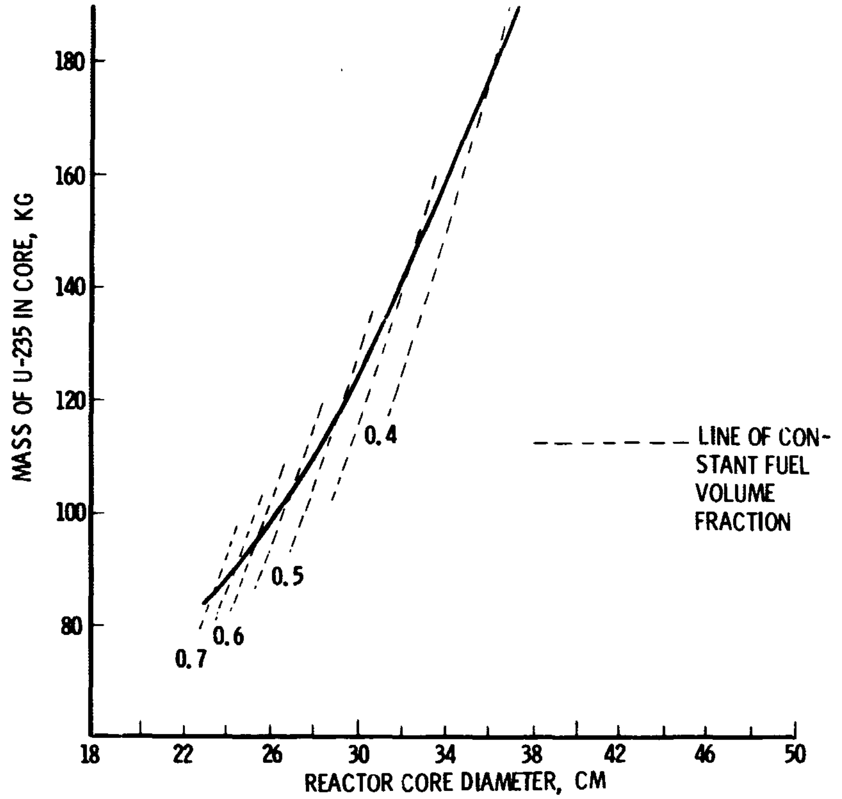

Figure 8. - Fuel mass and fuel volume required for criticality and burnup (approx. 5×10^4 hr).

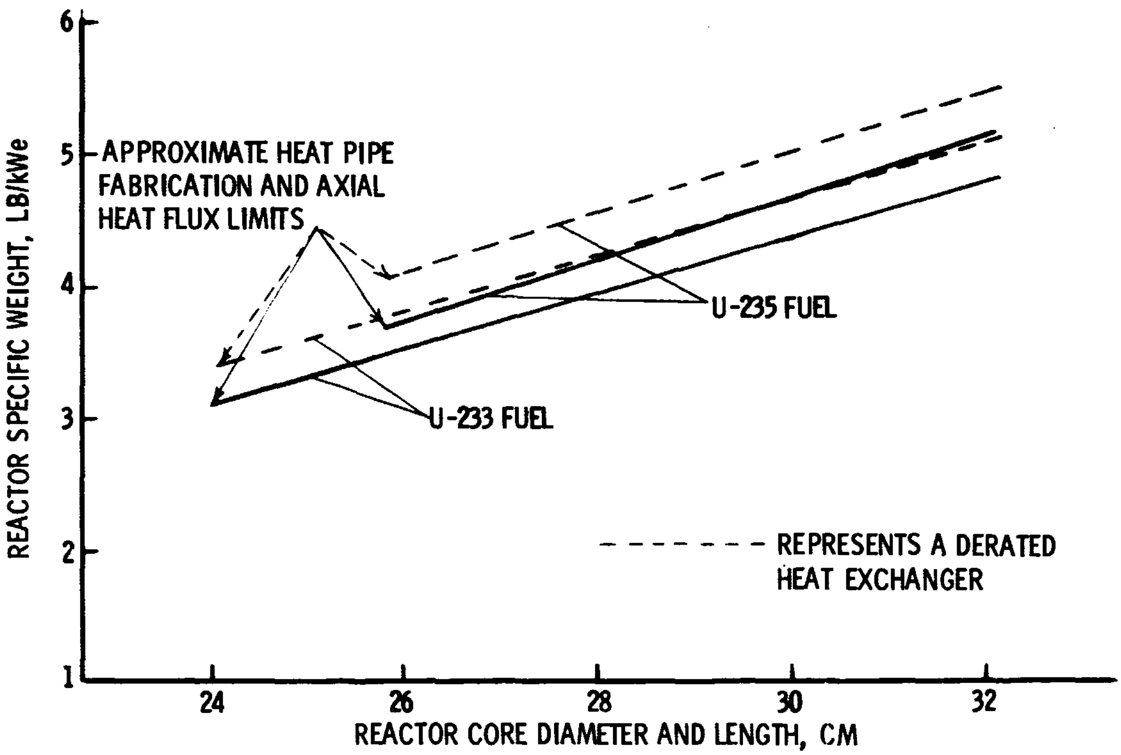

Figure 9. - Effect of core size on specific weight of reactor assembly.

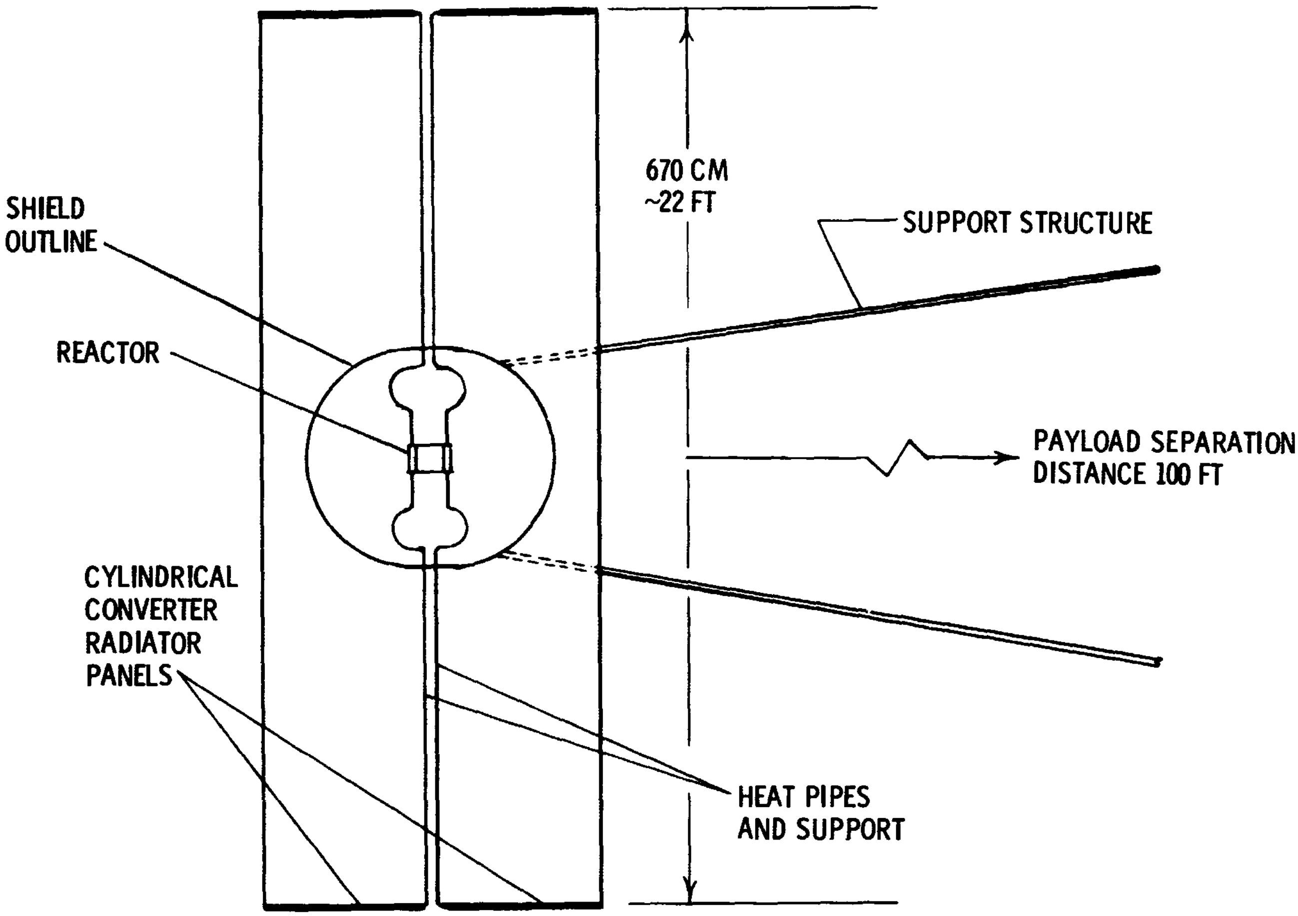

Figure 10. - An example of a 350 kWe, man rated, 4π shielded, nuclear reactor system using the out-of-core approach.

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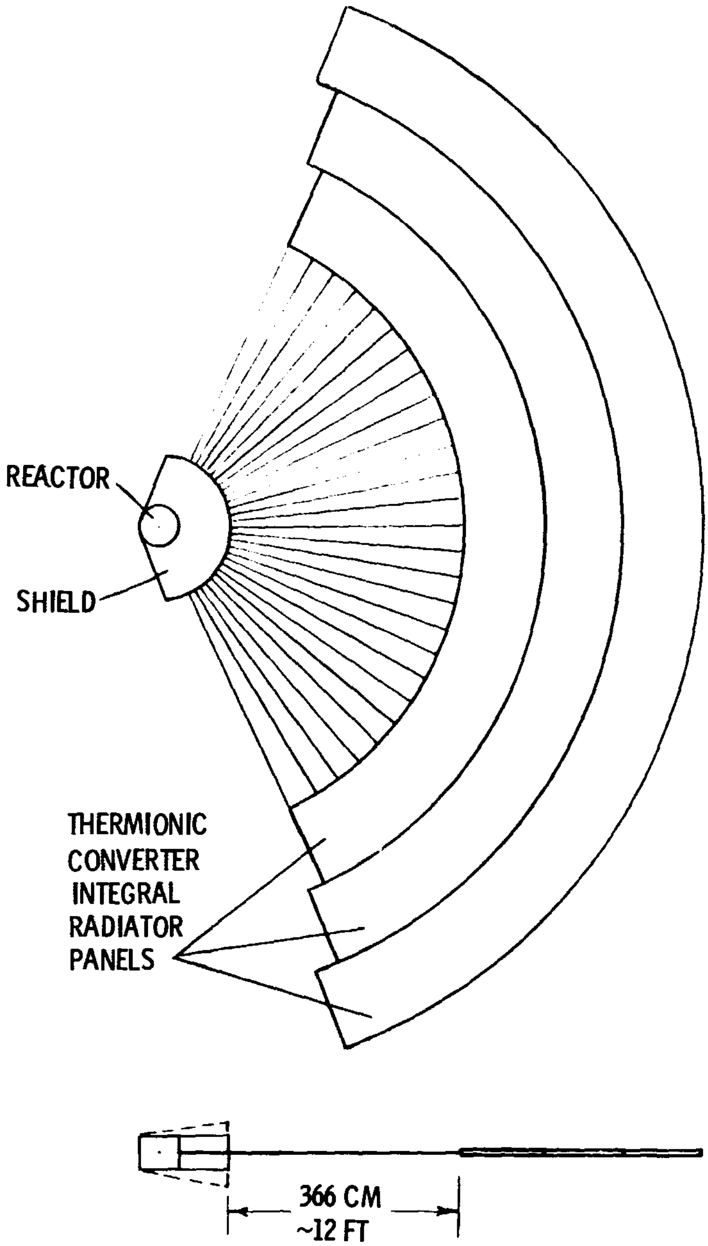

Figure 11. - An example of a 350 kWe, shadow shielded, instrument rated (1R/hr at 100 ft) out-of-core thermionic system.